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A Predictive Parametric Model for Volume Scattering Strength in the Deep Ocean With an Application to Nighttime Near-Surface Scattering in the North Sargasso Sea Below 16 kHz

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**Naval Undersea Warfare Center Detachment
New London, Connecticut**

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PREFACE

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A handwritten signature in cursive script, reading "B. F. Cole".

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13. ABSTRACT (Maximum 200 words) <p>In the deep ocean, long range active sonars are often volume reverberation limited at night due to scattering from the gas-filled swimbladders of mesopelagic fish in near-surface waters. To predict the detection performance of these sonars with a general sonar model, volume scattering strength profiles $S_V(z,f)$ are needed as inputs. A general volume scattering strength model (VSSM) for nighttime/daytime $S_V(z,f)$ profiles in a deep water faunal province is described. Explicit expressions are developed for the average length-depth distribution of bladdered fish, the corresponding swimbladder radius-depth distribution, and volume scattering strength $S_V(z,f)$. A specific nighttime near-surface VSSM is developed for the North Sargasso Sea faunal province using data from Ocean Acre experiment 12. A VSSM of very simple form is found capable of describing measured nighttime profiles at 3.85 and 15.5 kHz to a depth of 225 m. This agreement, however, could only be obtained by modifying model parameters obtained from trawl data to correct for sampling deficiencies, principally net avoidance by the larger fish. Predictions with the modified VSSM at 1 kHz suggest that in the nighttime 0-50 m surface layer, S_V-levels were as high as -75 dB due to scattering from these larger fish.</p>				
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A PREDICTIVE PARAMETRIC MODEL FOR VOLUME SCATTERING STRENGTH IN
THE DEEP OCEAN WITH AN APPLICATION TO NIGHTTIME NEAR-SURFACE
SCATTERING IN THE NORTH SARGASSO SEA BELOW 16 kHz

I. INTRODUCTION

In the deep ocean, volume reverberation below 20 kHz is caused principally by resonant and nonresonant scattering from the gas-filled swimbladders of numerous species of mesopelagic fish most of which are diel vertical migrators. At night, a significant fraction of these bladdered fish scatterers rise from daytime depths to feed on zooplankton in a 200 m subsurface layer. Under commonly occurring propagation conditions, these near-surface scattering layers can significantly lower the detection performance of long range 2-5 kHz search sonars. To predict the nighttime detection performance of such sonars for shallow targets, volume scattering strength profiles $S_v(z,f)$ for these layers must be provided as inputs to sonar performance prediction models. The objective is to show how S_v -profiles can be parametrically modeled in the deep ocean and, by way of illustration, develop a nighttime summer model for the North Sargasso Sea.

A predictive theoretical model for $S(z,f)$ requires submodels for the length-depth distribution of the scatterers, the swimbladder sizes they contain, and the scattering properties of the swimbladders. First we present a general theoretical model for predicting $S_v(z,f)$ in a deep water faunal province (Backus

and Craddock 1977). This model is then specifically tailored to describe nighttime near-surface volume scattering in the North Sargasso Sea during summer. Bioacoustic data from OA12, one of the most successful of the Ocean Acre experiments (Brown and Brooks, 1974), are used to formulate the model. We note here that the Ocean Acre measurement site is a 1-degree quadrangle southeast of Bermuda centered at 32°N, 64°W and that it is a "typical" location in the North Sargasso Sea faunal province (Brooks 1972, Backus and Craddock 1977).

The motivation for our parametric modeling approach stems in part from the limitations of discrete-depth biological sampling. In the Ocean Acre experiments (Brown and Brooks 1974, Gibbs et al. 1987), discrete-depth biological samples were obtained with a 3-m Isaacs Kidd Midwater Trawl (IKMT) and concurrent measurements of $S(z,f)$ for frequencies between 3.85 and 15.5 kHz were obtained with narrow-beam transducers (Fisch and Dullea 1973 and Fisch 1977). While the seasonal biological properties of bladdered fish at the Ocean Acre site have been qualitatively established by these trawl measurements, the data are inadequate for bioacoustic prediction, as found by Brown and Brooks (1974) and Brooks and Brown (1977). This is due to the sampling deficiencies of the IKMT caused by net avoidance and escapement, further complicated by patchiness and practical limitations on the volume of water that can be sampled at each depth.

As will be demonstrated, a "Trawl Based $S(z,f)$ Model" (TBSM) with parameters obtained directly from OA12N data leads to unsatisfactory agreement between predicted and measured values of

$S_v(z, f)$ at 3.85 kHz, as might be expected for the reasons given above. Because of the parametric nature of the VSSM, however, those parameters defining the theoretical length-depth distribution of the scatterers can be adjusted to compensate for sampling deficiencies. The "Modified TBSM" thus obtained will be shown to produce dramatically better agreement between predicted and measured S_v -profiles at 3.85 kHz and 15.5 kHz. S_v -predictions are also made at the nominal frequencies 0.5 and 1.0 kHz at which scattering from mesopelagic fish is commonly assumed to be negligible. The large differences between corresponding predictions with the two models at 3.85, 15.5, 0.5, and 1.0 kHz are physically explained with the help of a resonance frequency/depth diagram for the various life stage size classes of the bladdered fish population.

II. A PARAMETRIC PHYSICAL MODEL FOR PREDICTING VOLUME SCATTERING STRENGTH IN THE DEEP OCEAN (VSSM)

In section 2.1 we first formulate an idealized theoretical model for the length-depth distribution $n(L, z)$ of swimbladdered fish. The approach was suggested by the seasonal depth distribution patterns of bladdered fish observed in the Ocean Acre experiments which are believed to be fairly typical of many deep ocean areas. For bioacoustic modeling, the swimbladder radius-depth distribution $n(R, z)$ is required, and the procedure for transforming $n(L, z)$ to $n(R, z)$ is considered next. Then, in section 2.2, a general theoretical formulation for the volume backscatter coefficient $s_v(z, f)$ is given. It contains a simplified form of Andreeva's (1964, 1972) model for swimbladder

target strength in which contributions of heat loss to damping at resonance are ignored. The height of the swimbladder target strength resonance peak is determined by $Q(z)$, the inverse damping factor at resonance. Representative minimum, mean, and maximum values of $Q(z)$ in general accord with experimental values are proposed for S-predictions with the VSSM. These are obtained from the simplified form of Andreeva's formula for $Q(z)$, using suitable choices for the complex shear modulus of fish tissue.

2.1 Biological Modeling Methodology

Definitions of fish length-depth density distributions and associated variables. Consider the swimbladder fish population in some deep ocean faunal province during either nighttime (N) or daytime (D) periods when the distribution of the scatterers is approximately steady state due to the absence of substantial vertical migration. For simplicity, N/D distribution conditions are assumed to be spatially and temporally homogeneous over horizontal x,y planes for all depths of interest. We define the fish length-depth density distribution $n(L,z)$ such that $n(L,z)dLdz$ represents the average number of scatterers with lengths $L...L+dL$ at depths $z...z+dz$ below $1m^2$ of sea surface anywhere within the faunal province. It is convenient to refer this distribution to the average number of scatterers N below $1m^2$ of sea surface, the "standing crop," and write

$$(1) \quad n(L,z) = N\hat{n}(L,z)$$

where $\hat{n}(L,z)$ is the fish length-depth density distribution per unit standing crop. We assume that annual variations in seasonal

distribution properties are solely due to annual variations in the seasonal standing crop N . This permits us to interpret $\hat{n}(L,z)$ as a "characteristic" seasonally invariant measure of the N/D distribution properties of the faunal province.

The quantity $\hat{n}(L,z)$ may also be interpreted as a two dimensional probability density distribution function. From probability theory, we can write it as

$$(2) \quad \hat{n}(L,z) = \hat{n}(z)p(L|z),$$

where $\hat{n}(z)$ is a probability density function (pdf) in the depth variable z and $p(L|z)$ is the conditional L -pdf for depth z . The marginal L -pdf associated with $\hat{n}(L,z)$ is

$$(3) \quad p(L) = \int_0^{\infty} \hat{n}(L,z) dz ,$$

while its marginal z -pdf is

$$(4) \quad \hat{n}(z) = \int_0^{\infty} \hat{n}(L,z) dL .$$

The average number density $n(z)$, i.e., the average number of fish per unit volume at depth z , is given by

$$(5) \quad n(z) = N\hat{n}(z) .$$

Formulation for $n(L,z)$ in the VSSM. Over a given depth range of interest, $n(L,z)$ is expressed as a sum of density distributions $n_i(L,z)$ corresponding to $i=1,2,\dots$ different

"scattering layer components",

$$(6) \quad n(L,z) = \sum_i n_i(L,z) .$$

A scattering layer component may represent an individual bladdered fish species or a group of such species treated as a single "equivalent" bladdered species. Distribution properties of mesopelagic fish are size-dependent, which complicates biological modeling. Depending on the frequencies and depth range for which S_v is to be predicted, not all size classes of fish may be significant contributors to scattering. Restricting the size range of bladdered fish in scattering layer components to just those sizes of specific acoustic interest may simplify the modeling of $n_i(L,z)$ in some instances. Seasonal biological properties of the bladdered fish fauna, time-of-day, and the depths and frequency ranges for which $S_v(z,f)$ is to be predicted must all be considered in choosing the appropriate scattering layer components for any particular VSSM.

The distribution properties of the i^{th} scattering layer component are formally analogous to those of $n(L,z)$ described above. Letting N_i be the standing crop and $\hat{n}_i(L,z) = \hat{n}_i(z)p_i(L|z)$ the characteristic distribution of the i^{th} scattering layer component, we may write $n(L,z)$ as

$$(7) \quad n(L,z) = \sum_i N_i \hat{n}_i(z) p_i(L|z) .$$

The particular characteristic distributions $\hat{n}_i(L,z)$ employed in the prototype VSSM are briefly described as follows (see

Appendix A for details). Consider a positive valued variate $\theta > 0$ which is lognormally distributed. The lognormal pdf of θ , designated here by $\lambda(\theta; \mu, \sigma^2)$, is given by

$$(8) \quad \lambda(\theta; \mu, \sigma^2) = [\theta \sigma \sqrt{2\pi}]^{-1} \text{EXP} [-(2\sigma^2)^{-1}(\ln \theta - \mu)^2] ,$$

where μ and σ^2 are the parameters of the distribution. As shown in Appendix A, the characteristic distribution $\hat{n}_i(L, z) = \hat{n}_i(z) p_i(L|z)$ for an i^{th} scattering layer component is defined by five statistical parameters, $[\mu_i, \sigma_i^2, \mu_{xi}, \sigma_{xi}^2, \rho_i]$. In terms of these parameters,

$$(9) \quad \hat{n}_i(z) = \lambda(z; \mu_i, \sigma_i^2)$$

$$(10) \quad p_i(L|z) = \lambda\left(L; \mu_{xi} | \zeta, \sigma_{xi}^2 | \zeta\right) \\ = \lambda\left(L; \mu_{xi} + \rho_i \left(\frac{\sigma_{xi}}{\sigma_i}\right) [\zeta(z) - \mu_{xi}], \sigma_{xi}^2 [1 - \rho_i^2]\right)$$

where, in the first distribution parameter of $p_i(L|z)$, Eq. (10), $\zeta(z) = \ln(z/d)$, with $d=1$ m. When $\rho_i \neq 0$, some statistical properties of fish length such as the mean, e.g., vary systematically with z throughout the i^{th} layer, due to the change in form of $p_i(L|z)$ with depth. (Equations for the z -dependence of the mode, median, and mean of $p_i(L|z)$ are given in Appendix A.) If the random variates L and z are statistically independent for the i^{th}

scattering layer component, then $\rho_i=0$, and we have a "simple i^{th} scattering layer component". For such components, length distribution properties are independent of depth, as may be seen by putting $\rho_i=0$ in Eq. (10). Then the conditional pdf $p_i(L|z)$ reduces to the marginal pdf $p_i(L)=\lambda(L;\mu_{xi},\sigma_{xi}^2)$, Eq. (A2), in Appendix A. This length pdf and all statistical properties associated with it remain the same at all depths throughout the i^{th} simple scattering layer component.

If the scattering layer components of $n(L,z)$ are all simple layers, then $n(L,z)$ in Eq. (7) becomes

$$(11) \quad \begin{aligned} n(L,z) &= \sum_i N_i \hat{n}_i(z) p_i(L) \\ &= \sum_i N_i \lambda(z;\mu_i,\sigma_i^2) \lambda(L;\mu_{xi},\sigma_{xi}^2) . \end{aligned}$$

The characteristic distribution $\hat{n}_i(L,z)$ for each i^{th} simple layer is specified by four parameters, $[\mu_i,\sigma_i,\mu_{xi},\sigma_{xi}]$ and the scale of its contribution to $n(L,z)$ is set by the layer standing crop factor N_i .

Transformation of $n(L,z)$ to $n(R,z)$. Each bladdered mesopelagic fish of length L is assumed to contain a fully inflated swimbladder with an equivalent spherical radius R . Replacing L by R in Eqs. (7) and (11) for $n(L,z)$, we have the corresponding formal expressions

$$(12) \quad n(R,z) = \sum_i N_i \hat{n}_i(z) q_i(R|z)$$

and

$$(13) \quad n(R,z) = \sum_i N_i \hat{n}_i(z) q_i(R)$$

for $n(R,z)$. To obtain explicit expressions for $n(R,z)$ in these equations, transformations $p_i(L|z) \rightarrow q_i(R|z)$ and $p_i(L) \rightarrow q_i(R)$ must be performed.

Due to swimbladder size variability in mesopelagic fish, it is desirable for purposes of transformation to use a more realistic swimbladder size allometry model than that afforded by an allometric law regression curve $R=aL^b$. Bivariate normal models are available for Ocean Acre bladdered species and bladdered species groups (Saenger 1989). If such models are used as a basis for transformation, then it can be shown (Saenger 1988) that $q_i(R|z)$ is a lognormal pdf with distribution parameters depending on the parameters $\mu_{xi|\zeta}$ and $\sigma_{xi|\zeta}^2$ of $p_i(L|z)$, Eq. (10), and other quantities:

$$(14) \quad q_i(R|z) = \lambda(R; \mu_{yi|\zeta}, \sigma_{yi|\zeta}^2)$$

with

$$(15) \quad \mu_{yi|\zeta} = \ln a + b\mu_{xi|\zeta}$$

and

$$(16) \quad \sigma_{yi|\zeta}^2 = b^2 \sigma_{xi|\zeta}^2 + s_{y|x}^2,$$

where a and b refer to the allometric law curve $R=aL^b$ associated with the bivariate model, and $s_{y|x}^2$ is a constant obtained from the model that, simply put, expresses the spread of swimbladder size about the regression curve. For the special case $\rho_i=0$,

where we are dealing with a simple scattering layer, the transformed distribution $q_i(R)$ obtained from $p_i(L)$, Eq. (A2), is also lognormal, and is given by

$$(17) \quad q_i(R) = \lambda(R; \mu_{yi}, \sigma_{yi}^2) ,$$

with

$$(18) \quad \mu_{yi} = \ln a + b\mu_{xi}$$

and

$$(19) \quad \sigma_{yi}^2 = b^2 \sigma_{xi}^2 + s_{y|x}^2 .$$

Swimbladder variability extends the frequency bandwidth of the scattering so, if possible, it should be taken into account to reduce prediction errors in S_v . (See Saenger 1988 for discussion and examples).

2.2 Bioacoustic Modeling Methodology

The volume backscatter coefficient $s_v(z, f)$. Randomly dispersed or loosely aggregated bladdered fish are assumed so that scattering contributions from individual swimbladders may be summed incoherently. Following conventions introduced by Urick (1983), the volume backscatter coefficient $s_v(z, f)$ may be expressed as

$$(20) \quad s_v(z, f) = n(z)\tau(z, f)/d^2, \text{ m}^{-3}$$

where $\tau(z, f)$ is the average target strength in m^2 of swimbladders

of all size found at depth z for an ensonifying frequency f . (Some prefer to omit $d^2 = 4\pi^2$ from this definition, in which case the resulting volume backscatter coefficient $m_v(z, f)$ has dimensions d^{-1} .) From probability theory, $\tau(z, f)$ is computed from

$$(21) \quad \tau(z, f) = \int_0^{\infty} q(R|z) \tau_0(R, z, f) dR, \quad m^2$$

where $\tau_0(R, z, f)$ is the target strength in m^2 of a gas-filled swimbladder of radius R cm at depth z for frequency f . Combining Eqs. (20) and (21) and remembering that $n(z)q(R|z) = n(R, z) = N\hat{n}(R, z)$, s_v may be written as

$$(22) \quad s_v(z, f) = N \int_0^{\infty} \hat{n}(R, z) [\tau_0(R, z, f)/d^2] dR \\ = N \hat{s}_v(z, f)$$

where $\hat{s}_v(z, f)$ in m^{-1} is the volume backscatter coefficient per unit standing crop. This expression points up the central importance of the characteristic swimbladder radius-depth distribution $\hat{n}(R, z)$ as a biological input. It follows from our biological assumptions that $\hat{s}_v(z, f)$ is an invariant characteristic measure of seasonal volume scattering properties in the faunal province.

The volume scattering contribution $s_{vi}(z, f)$ from each i^{th} scattering layer component has a form similar to that for $s_v(z, f)$ in Eq. (22), viz.,

$$(23) \quad s_{vi}(z, f) = N_i \hat{s}_{vi}(z, f) .$$

Due to the assumption of incoherent scattering, s_{vi} -contributions from each i^{th} component can be added to give $s_v(z, f)$. With L and R in cm and z in m, the formal theoretical expressions for $S_v(z, f)$ in the VSSM are summarized as follows:

$$(24) \quad S_v(z, f) = 10 \log [s_v(z, f)d^3], \text{ dB re } 1/\text{m}^3$$

$$(25) \quad s_v(z, f) = \sum_i N_i \hat{s}_{vi}(z, f), \text{ m}^{-3}$$

$$(26) \quad \hat{s}_{vi}(z, f) = \hat{h}_i(z) \int_0^{\infty} q_i(R|z) [\tau_0(R, z, f)/d^2] dR, \text{ m}^{-1}$$

$$(27) \quad \hat{h}_i(z) = \lambda(z; \mu_i, \sigma_i^2), \text{ m}^{-1}$$

$$(28) \quad q_i(R|z) = \lambda(R; \mu_{yi}|z, \sigma_{yi}^2|z), \text{ cm}^{-1} .$$

For a simple i^{th} scattering layer component, $q_i(R|z)$ in Eqs. (26) and (28) is replaced by $q_i(R)$ given in Eq. (17). At present, full computer implementation of these equations exists only for simple scattering layer components. In numerically calculating $\hat{s}_{vi}(z, f)$, Eq. (26), for such a component, digitally sampled, truncated, and renormalized pdfs $\hat{h}_i(z)$ and $q_i(R)$ are used, and the integral is evaluated using the trapezoid rule.

The simplified Andreeva model for swimbladder target strength. In the VSSM, a simplified form of Andreeva's (1964, 1972) model for swimbladder target strength $\tau_0(R, z, f)$ is used in which only radiation and viscous damping losses are retained in the theoretical expression for $Q(z)$, the reciprocal damping

constant at resonance. The equations of this model as used in the VSSM are summarized in Appendix B.

In modeling volume scattering strength in the deep ocean, it is not possible to measure the many variables that determine the Q of fish swimbladders. Therefore, in the context of the simplified Andreeva model, we propose the adoption of provisional phenomenological values for the complex shear modulus $\mu = \mu_r + i\mu_{im}$ of fish tissue that give values of Q in reasonable agreement with experiment. Some available experimental data are shown in Table 1. Measurements of $Q(z)$ made near the surface are of the order of 3 to 5. Assuming such results are applicable to mesopelagic fish, and taking $\mu_r = 1(10^6)$ dyn/cm² as recommended by Batzler and Pickwell (1970), $Q(z)$ was computed from Eq. B(10) using different values of μ_{im} . By trial-and-error, the "Representative Minimum, Mean, and Maximum $Q(z)$ curves shown in figure 1 were obtained. These curves encompass many of the $Q(z)$ values in Table 1, and the trends of the theoretical $Q(z)$ curves with depth are at least consistent with the observations of McCartney and Stubbs (1971). VSSM predictions displayed below utilize one or other of these $Q(z)$ curves, as noted.

III. A SUMMER NIGHTTIME VSSM FOR NEAR-SURFACE WATERS OF THE NORTH SARGASSO SEA APPLICABLE FOR LOW SONAR SEARCH FREQUENCIES

The VSSM provides a general formalism for modeling the length-depth distribution $n(L,z)$ of biological scatterers in a faunal province. The objective here is to select the simplest

Table 1. Swimbladder resonance frequency and Q measured for various live swimbladdered fish with swimbladders believed to be intact.

Fish	Length, cm	Depth, m	f_0 , kHz	Q	Source of Data/Comments
(1) Anchovy	10.6	6	1275	4.5	Batzler, and Pickrell, 1970: $\mu = 1(10^6)$ dyn/cm ² is optimum or near optimum for predicting swimbladder resonance frequencies from Andreeva's formula, Eq. (B5).
Coalfish	29.5	30	950	2.5	McCartney and Stubbs, 1971: Q
Ling	55	30	500	2.5	consistently decreased as fish were raised to shallower depths, and
(2) Cod	32;35	30	910;560	3.5;2.0	consistently increased as fish were lowered to greater depths.
Pollack	35	30	766	~1	
(3) Coalfish	7.7	4	1950	2.5	Løvik and Hoven, 1979: Used the measurement technique of McCartney and Stubbs, 1971. Measurements made on live fish that were apparently healthy after the experiment.
		12	2200	2.9	Depth-adapted values for f_0 and Q.
		32	3200	2.3	
		44	3600	2.8	
Sprat	16.0	4	900	2.5	
Herring	28.5	4	750	2.0	
Cod	26.5	4	1000	1.1	

(1) The example given is claimed to be "typical" of Q values between 3 and 5 obtained from measurements on anchovy and goldfish.

(2) Condition of bladder uncertain - fish escaped.

(3) For this single specimen, f_0 and Q are adapted values at each depth.

Plot of $Q(z)$ - Simplified Andreeva Model

MU-R, dynes/cm² 1.000D+06 1.000D+06 1.000D+06

MU-IM, dynes/cm² 2.500D+06 1.500D+06 1.000D+06

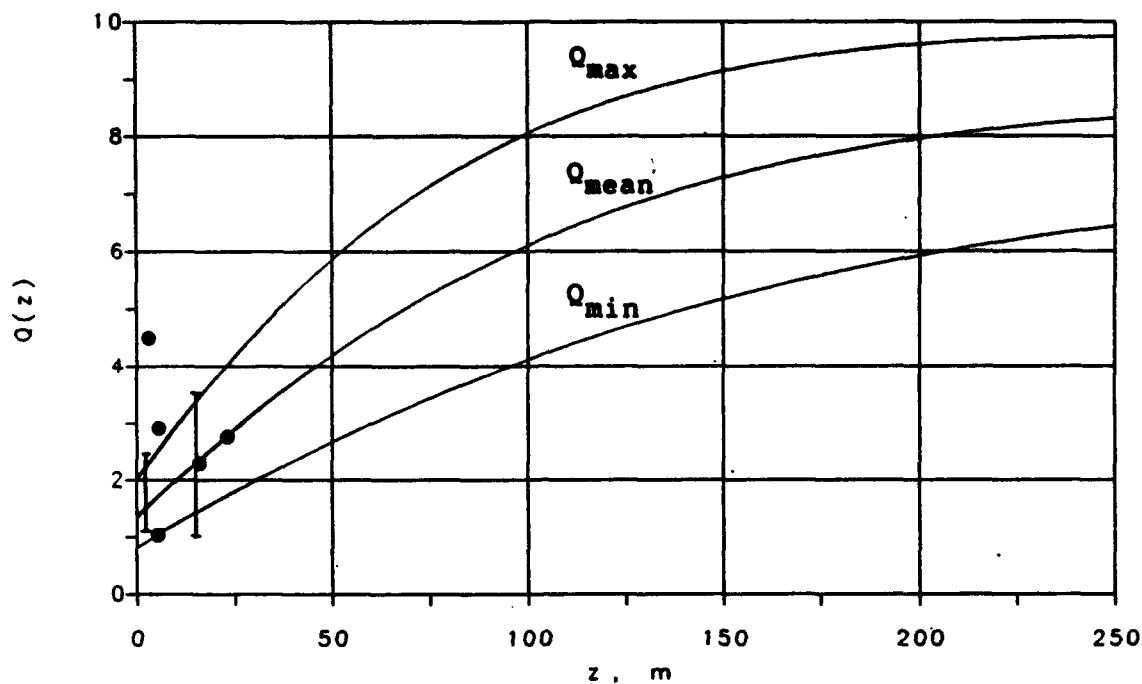


Figure 1. Representative theoretical $Q(z)_{min}$, $Q(z)_{mean}$, and $Q(z)_{max}$ curves based on a simplified form of Andreeva's (1964, 1972) model that includes only radiation and viscous damping losses. Respective values of $\mu = \mu_r + i\mu_{im}$ used to generate these curves are shown in the header. Experimental data from Table 1 are included.

model capable of predicting $S(z,f)$ between the surface and a depth of the order of 200 m for sonar frequencies up to about 15 kHz. This requires consideration of the broad features of OA12N biological data and their physical implications. Unfortunately, average trends in the length-depth distributions of bladdered fish are obscured by the unknown efficiency of the IKMT net and sampling fluctuations accentuated by the low densities of bladdered fish and patchiness. Consequently, the choice of model is somewhat subjective. The ultimate justification for any particular model is that it involve as few theoretical parameters as possible and that it is capable of predicting experimental values of $S(z,f)$. In the section below, a very simple model for $n(L,z)$ is proposed based on distribution properties inferred from OA12N trawl data. Predictions with this model are made in the following section where it is shown that, due primarily to net avoidance by the larger fish, model parameters derived from trawl data must be modified to obtain realistic predictions.

3.1 Biological Conditions at Ocean Acre and the Selection of a VSSM

Using trawl data from the major Ocean Acre experiments together with swimbladder size allometry information, Brown and Brooks (1974) identified 55 predominant swimbladdered fish taxa at Ocean Acre. The size-depth distribution properties of these fish during the spring (OA10,14), summer (OA12), and winter (OA13) were studied in detail by Brooks and Saenger (1991). In the OA12N nighttime 0-200 m layer, these fish have individual

overlapping depth niches and a wide range of fish size is found at each depth. This configuration is believed to represent a basic ecological strategy for reducing competition for zooplankton food resources during nighttime feeding periods. Because of the small numbers caught, length-depth distributions of individual bladdered fish species are ill-defined experimentally so a "species group" approach to bioacoustic modeling is necessary.

Brooks and Saenger (1991) found that 18 particular predominant bladdered species taken as a group had diel length-depth distribution properties that closely represent the distribution properties of the entire night/day catches of swimbladdered fish at Ocean Acre in spring, summer and winter. This 18 predominant bladdered species group (18PBSG) was partitioned into larval-postlarval (L/PL), juvenile (J), subadult (SA), and adult life-stage size classes. In OA12, the nighttime composition of the 18PBSG group found between the surface and a depth of 225 m was L/PL(40.5%), J(43.5%), SA(14.5%), and A(1.5%). The characteristic density distribution $\hat{n}_s(z)$ for each life stage size class, normalized with respect to the 0-225 m depth interval, is unimodal and the distributions for all size classes are fairly similar. Also, the experimental fish length distributions $p(L|z_k)$ at the sample depths $z_k=25, 125, 175$, and 225 m are unimodal and do not appear to depend strongly on depth. (No 18PBSG fish were taken at $z_k=0$.) On the basis of this subjective identification of major trends in the trawl data, it is proposed that $n(L,z)$ for the 18PBSG be modeled as a simple scattering layer taking

$$\begin{aligned}
 (29) \quad n(L,z) &= N\hat{n}(z)p(L) \\
 &= N\lambda(z;\mu,\sigma^2)\lambda(L;\mu_x,\sigma_x^2) .
 \end{aligned}$$

Further, to represent the swimbladder size allometry properties of this group, it seems most appropriate to use an "equivalent bivariate normal" model developed by Saenger (1989) for a subgroup of 50 Ocean Acre nonregressive swimbladdered fish taxa drawn from the list of 55 OA predominant swimbladdered fish taxa given by Brown and Brooks (1974). Regression equation constants (a,b) and $s_{y|x}^2$ from this model are found at the bottom of Table 2 below. The swimbladder radius-depth distribution corresponding to $n(L,z)$ in Eq. (29) is $n(R,z)=N\hat{n}(z)q(R)$, and the parameters (μ_y,σ_y^2) of the lognormal pdf $q(R)$ are obtained from those of $p(L)$ using Eqs. (18) and (19). Finally, the expression for $s_v(z,f)$ in this VSSM is obtained by substituting $N\hat{n}(z)q(R)$ for $N\hat{n}(R,z)$ in Eq. (22).

Physical implications and possible limitations of this very simple model are conveniently discussed with the help of figure 2, a resonance frequency/depth diagram for the different size classes. The 9 cm representative upper bound for the A class is suggested by modeling results in the next section. Nominal L-boundary values between each size class were transformed to corresponding R-values using $R=aL^b$, and resonance frequencies $f_0(R,z)$ were then plotted as a function of depth using Andreeva's formula, Eq. (B5). From Eq. (29) it is seen that $N\hat{n}(z)$ represents the average number of bladdered fish of all sizes at depth z . The relative proportions of the different size classes

Swimbladder Resonance Frequency vs z for Various Fish Lengths L

L(cm) 1.350D+00 2.250D+00 3.350D+00 9.000D+00

Parameters: a = 3.384D-02 b = 8.919D-01 MU-R = 1.000D+06 dynes/cm²

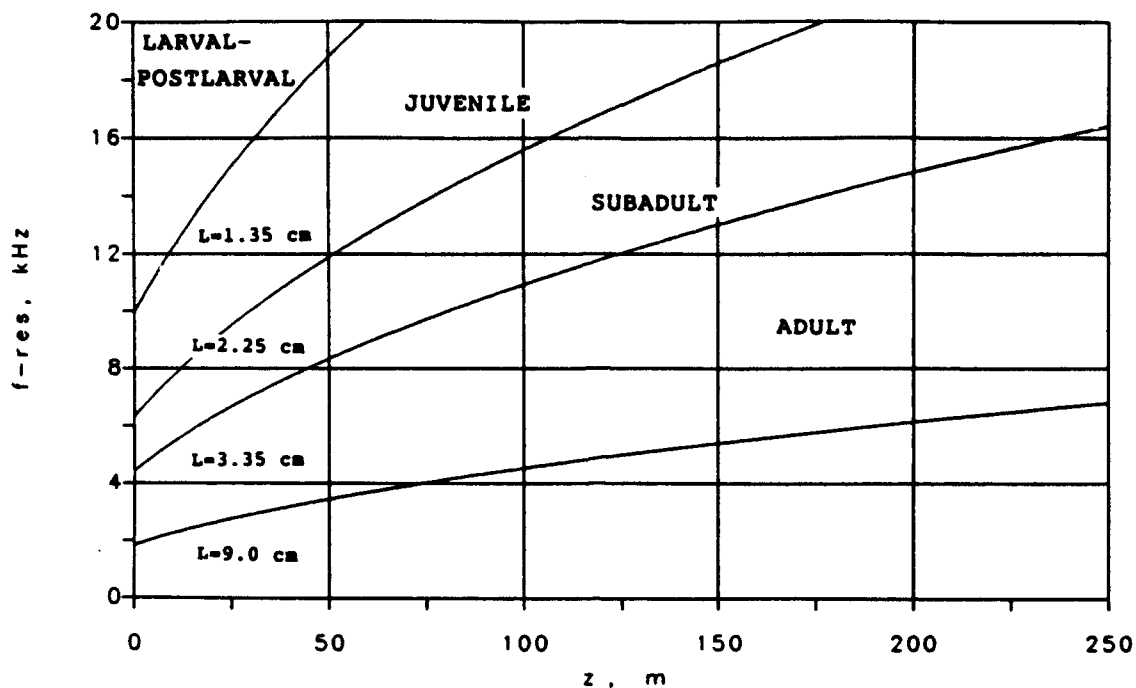


Figure 2. Resonance frequency vs depth domains for scatterers in the nominal life stage size classes of the Ocean Acre 18 predominant bladdered species group.

are determined by $p(L)$ and are the same at each depth in this model. For a given sonar frequency f , contributions to $S_v(z, f)$ from fish of a particular size will be greatest at those depths where the resonance frequency $f_0(R, z)$ of their swimbladders is equal to, or near, f . Since $\tau_0(R, z, f_0) \propto Q^2 R^2$ from Eq. (B3), such contributions from large fish at low kHz frequencies can be very important, even when these fish are present in relatively low numbers. Therefore the accuracy of low frequency predictions with this VSSM depends critically on the tail portion of the model pdf $p(L)$.

The size pass band limitations of the IKMT and the expected large summer increase of L/PL fish at Ocean Acre must both be considered in assessing the probable effectiveness of the proposed model for $n(L, z)$. Gibbs and Karnella (1987) tentatively estimated the range of fish size efficiently sampled by the 3-m IKMT to be 1-5 cm. With regard to the larger fish, comparison of OA12N non-discrete depth oblique catches with the much larger Engel trawl suggest that adult fish are inadequately represented in the IKMT catches. Brooks and Brown (1978) reported that while the range of fish size obtained with both nets was similar, the mean lengths of fish caught with the Engel trawl were commonly twice as large. In particular (private communication), they found the nighttime size distribution for a group of 6 species (which incidentally happen to belong to the 18PBSG) to be unimodal, with the mode of the IKMT distribution at 1.2 cm and that for the Engel distribution at 2.6 cm. Thus, it is very probable that the larger adult fish are not present in the IKMT catch. Also, it is very probable that the L/PL size class is

undersampled, since the estimated decrease in catch efficiency of the IKMT occurs over much of the L/PL size range.

If the summertime L/PL size class is actually a larger fraction of the 18PBSG than is indicated by the IKMT catch, it might be necessary to use a more general $n(L,z)$ model than that proposed in Eq. 29. In view of the size-dependent differences in life style expected of the L/PL and (J+SA+A) size groups, one might treat these size groups as independent scattering layer components. Or, individual size classes might be treated as independent scattering layer components in an even more refined model. However, trawl data provide no definitive evidence for the need of one or other of these more complex models, so we shall explore the predictive capability of the single scattering layer component model, the simplest of the various possible VSSMs.

3.2 Predictions with the Single Scattering Layer Component VSSM

The Trawl-Based S Model (TBSM). Predictions in the TBSM are made with model parameters derived solely from OA12N IKMT sample data for the 18PBSG taken at the depths $z_k=0, 25, 125, 175,$ and 225 m. No attempt has been made to correct the parameters for sampling deficiencies. $[N, \mu, \sigma^2, \mu_x, \sigma_x^2]$ were calculated as follows. Estimates of N and the moments \bar{z} and $\overline{z^2}$ of the experimental normalized density distribution referred to the 0-225 m depth interval were obtained using procedures described in Brooks and Saenger 1991. The parameters (μ, σ^2) of $\hat{n}(z)$ were then derived from \bar{z} and $\overline{z^2}$ by the method of moments (Aitchison

and Brown 1957). The parameters (μ_x, σ_x^2) of $p(L)$ were computed as density-weighted averages of $[\mu_x(z_k), \sigma_x^2(z_k)]$. The latter were calculated by applying the method of moments to experimental values of $\bar{L}(z_k)$ and $\overline{L^2}(z_k)$. Then the parameters (μ_y, σ_y^2) defining $q(R)$ were obtained from (μ_x, σ_x^2) using Eqs. (18) and (19) with allometric constants a, b , and $s_{y|x}^2$ from the 50 swimbladdered fish taxa bivariate normal model mentioned above. Table 2 contains the TBSM parameters so obtained and some statistical properties of the distributions $\hat{n}(z)$ and $p(L)$.

TBSM predictions $S(z, f)_{Qmin}$ and $S(z, f)_{Qmax}$ for 3.85 kHz are compared with OA12N experimental S_v -profiles obtained on two successive nights by Fisch and Dullea (1973) in Fig. (3a). The agreement is very poor. From our previous considerations, some of the shortfall in overall level may be supposed due to the model value for standing crop N being too low. However, the increasing divergence of the depth trend of predicted and experimental values is consistent with the expectation that important scattering contributions from larger fish are missing from the model. As seen from figure 2, contributions from adult fish are expected to be sizable at 3.85 kHz, not only because of the large size of their swimbladders, but because scattering occurs at a frequency equal to, or not too far from, the resonance frequency of their swimbladders.

At 15.5 kHz, Fig. (3b), agreement with experiment is still poor, but there is now less discrepancy in overall level and depth trends of predicted and experimental values. From figure 2, this may be tentatively explained by noting that at this

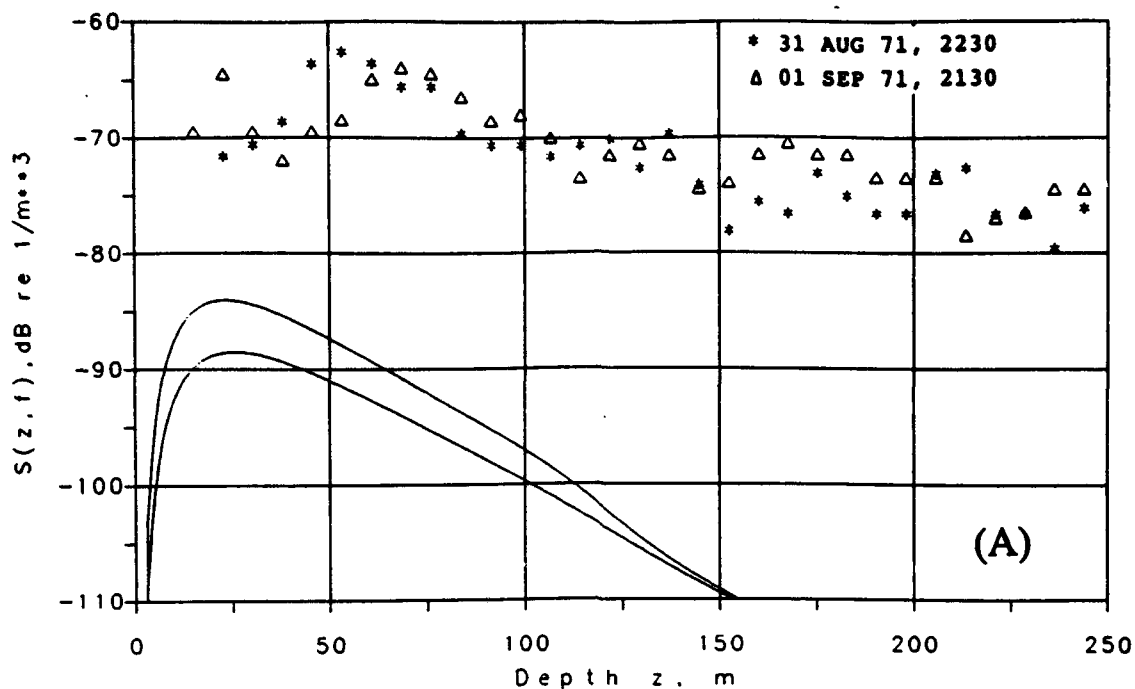
Table 2. Parameters and statistical properties of the lognormal pdfs used in the Trawl-Based $S_v(z, f)$ Model (TBSM) and the Modified TBSM.*

	TBSM, OA12N			Modified TBSM, OA12N	
	$\hat{h}(z), z^{-1}$	$p(L), \text{cm}^{-1}$	$q(R), \text{cm}^{-1}$	$\dot{p}(L), \text{cm}^{-1}$	$\dot{q}(R), \text{cm}^{-1}$
MU	3.929	0.444	-2.990	0.9902	-2.503
SIGMA	0.7466	0.3372	0.4595	0.6159	0.6500
Mode	29.1 m	1.39 cm	0.041 cm	1.84	0.054
Median	50.9 m	1.56 cm	0.050 cm	2.69	0.082
Mean	67.2 m	1.65 cm	0.056 cm	3.25	0.101
Stan. Dev.	58.0 m	0.57 cm	0.027 cm	2.21	0.073
Coef. of Var.	0.8638	0.3470	0.4849	0.6792	0.7251
2.5% fractile	11.8 m	0.81 cm	0.020 cm	0.80	0.023
97.5% fractile	219.7 m	3.02 cm	0.124 cm	9.00	0.293

*Notes 1. In the TBSM, a standing crop value $N=0.72/\text{m}^2$ was calculated from trawl data. In the Modified TBSM, a standing crop value $\hat{N}=4.93/\text{m}^2$ was calculated using experimental S_v - data at 3.85 kHz (see text).

2. Eqs. (18) and (19) were used to transform $p(L)$ to $q(R)$ and $\dot{p}(L)$ to $\dot{q}(R)$ with $a=3.384(10^{-2})$, $b=0.8919$, and $s^2_{y|x}=0.1207$ (Ocean Acre 50 nonregressive bladdered fish taxa model).

OA12N TRAWL-BASED $S(z, f)$ PREDICTION MODEL, $f=3.85$ kHz
COMPARISON OF EXPERIMENTAL WITH MINIMUM AND MAXIMUM PREDICTED VALUES



OA12N TRAWL-BASED $S(z, f)$ PREDICTION MODEL, $f=15.5$ kHz
COMPARISON OF EXPERIMENTAL WITH MINIMUM AND MAXIMUM PREDICTED VALUES

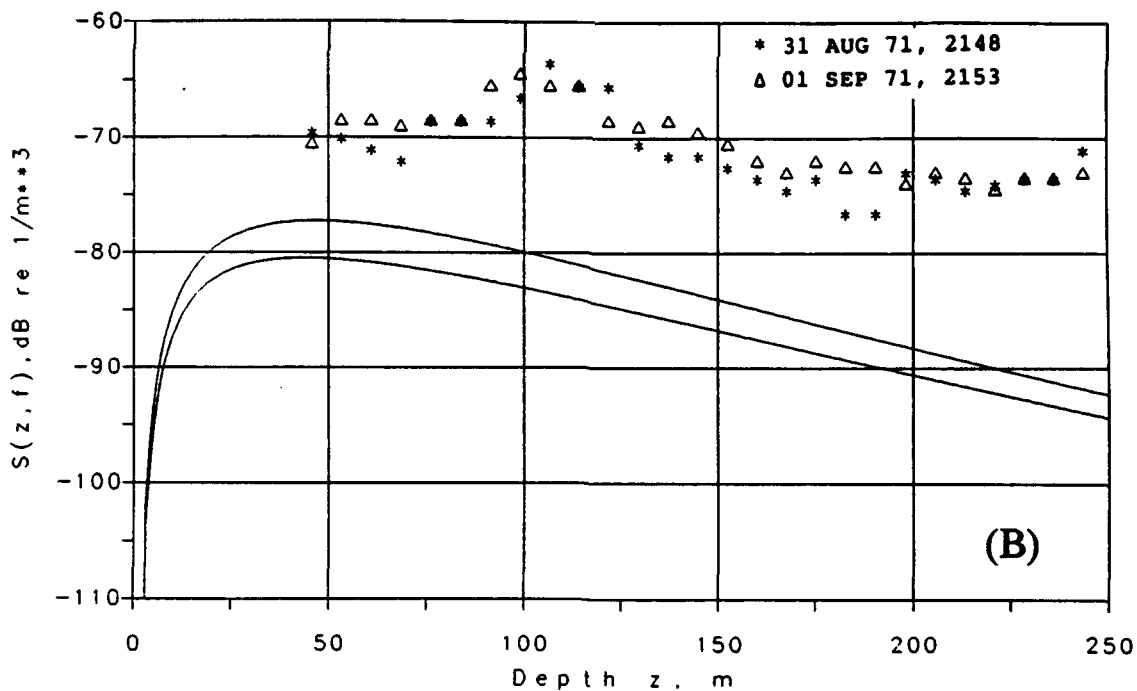


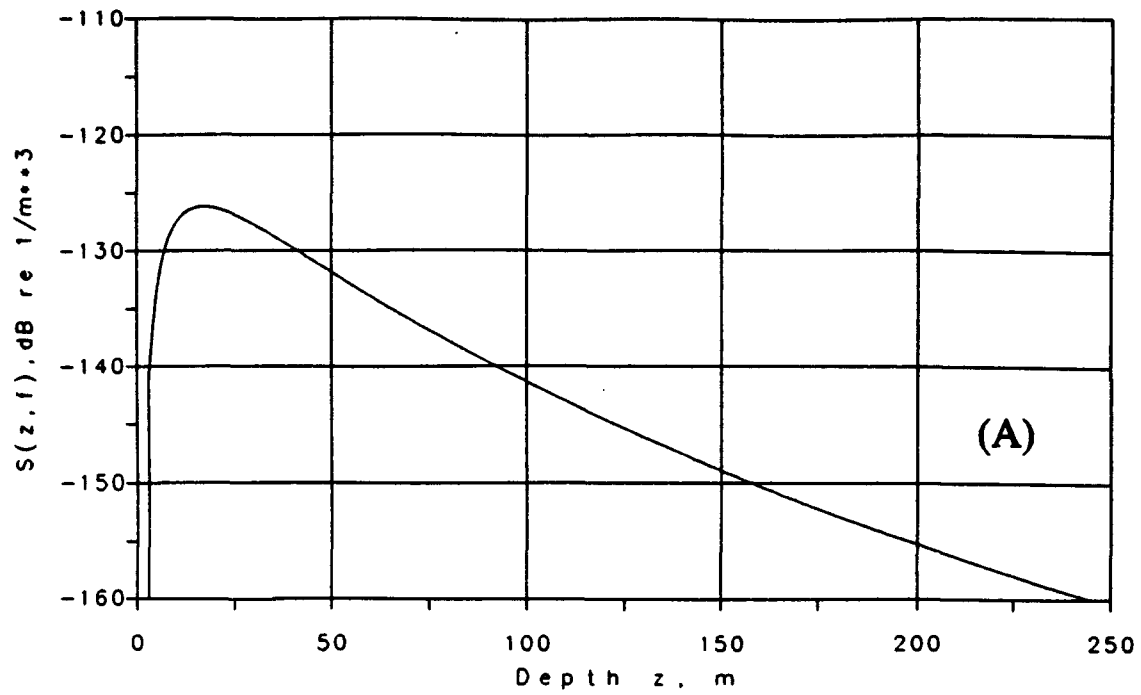
Figure 3. TBSM predictions of nighttime $S_v(z, f)_{Q_{\min}}$ (lower curve) and $S_v(z, f)_{Q_{\max}}$ (upper curve) compared with OA12N experimental profiles of Fisch and Dullea (1973) taken approximately 24 hours apart: Fig. (3a), $f=3.85$ kHz; Fig. (3b), $f=15.5$ kHz.

higher frequency, and for the depths where comparison is possible, dominant scattering contributions very likely came from J and SA fish that on the whole are expected to have been sampled more efficiently.

TBSM predictions for $f=0.5$ and 1.0 kHz are shown in figures (4a) and (4b), respectively. In each plot, the two curves are practically identical, since Q does not affect the form of $S_v(z, f)$ at these low frequencies. Here Rayleigh-type scattering is occurring so, in m^2 , $\tau_0(R, z, f) \approx 10^{-4} (f/f_0)^4 R^2$, with R in cm. This explains the systematic 12 db difference in predicted values of $S_v(z, f)$ at the two frequencies. The lowness of the predicted levels is presumably caused by the absence of scattering contributions from the larger fish that would be the dominant contributors to S_v at these low frequencies.

A Modified TBSM with model parameters corrected for net sampling deficiencies. The choice of TBSM parameters requiring modification to obtain agreement of VSSM predictions with experiment involves a number of physical considerations. First, it seems reasonable to assume that $\hat{n}(z)$ obtained from the TBSM provides a reasonable approximation for the actual characteristic density distribution. This assumption is prompted by the following observations: 1) $\hat{n}(z)$ can be expressed as a sum of contributions $(N_s/N)\hat{n}_s(z)$ from each s^{th} size class, where N_s is the standing crop of the s^{th} size class; 2) $\hat{n}_s(z) = n_s(z)/N_s$, by its definition, tends to be independent of a net sampling efficiency factor for the s^{th} size class; 3) $\hat{n}_s(z)$ for the L/PL and J size classes are virtually identical; and 4) these two size

RANGE OF OA12N TRAWL-BASED $S(z, f)$ PREDICTIONS FOR $f=0.5$ kHz



RANGE OF OA12N TRAWL-BASED $S(z, f)$ PREDICTIONS FOR $f=1$

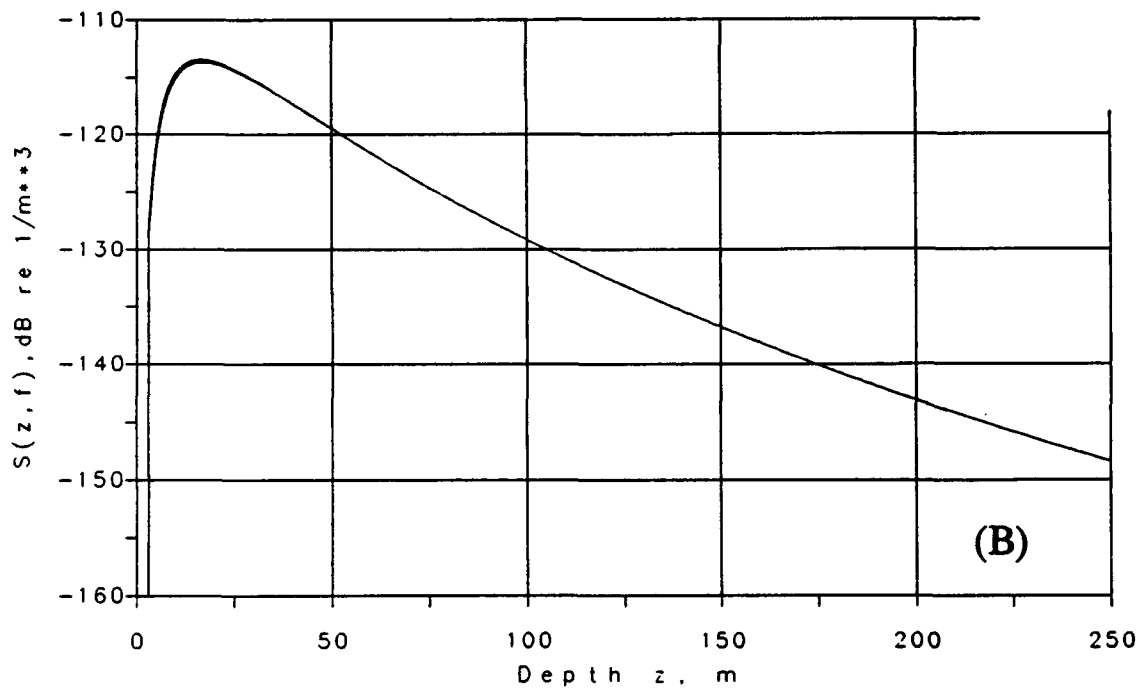


Figure 4. TBSM predictions of nighttime $S_v(z, f)_{Qmin}$ and $S_v(z, f)_{Qmax}$ for $f=0.5$ kHz (Fig. 3a) and $f=1.0$ kHz (Fig. 3b).

classes constitute 84% of the 18PBSG catch between the surface and 225 m depth. Assuming, then, that (μ, σ^2) are adequate, only the parameters (N, μ_x, σ_x^2) need modification. In estimating these parameters, we primarily utilize experimental S_v -data at 3.85 kHz, the lowest frequency for which experimental data from OA12N are available, since scattering contributions from larger fish missed by the IKMT are best represented in this data.

The average length-depth density in the Modified TBSM is designated by

$$(30) \quad \begin{aligned} \dot{n}(L, z) &= \dot{N} \dot{\hat{A}}(z) \dot{p}(L) \\ &= \dot{N} \lambda(z; \mu, \sigma^2) \lambda(L; \dot{\mu}_x, \dot{\sigma}_x^2) . \end{aligned}$$

The parameters of $\dot{p}(L)$ were obtained by systematically modifying those of $p(L)$ in such a way as to increase the relative proportion of larger fish in the distribution without unduly suppressing the smaller size class components. This was done by successively increasing the 3 cm 97.5% fractile point of $p(L)$ to 6 cm, 9 cm, 15 cm... The corresponding transformed pdfs $\dot{q}(R)$ were used to predict $\hat{S}(z, f)_{Qmean}$ at 3.85 and 15.5 kHz. For each case, the standing crop parameter \dot{N} was obtained by equating interval column strengths for the 23-221 m depth interval computed from the predicted and experimental 3.85 kHz S_v -profiles. Selection of the "optimum" Modified TBSM was necessarily somewhat subjective. Properties satisfied by the model finally chosen were the following:

1. Physical reasonableness of the 97.5% fractile points of the $\dot{p}(L)$ and $\dot{q}(R)$ distributions;
2. Acceptable agreement in the depth trends of 3.85 kHz $\hat{S}_v(z, f)_{Q_{mean}}$ and experimental S_v -profiles, apart from absolute levels;
3. \dot{N} such as to give better agreement in predicted levels at 15.5 kHz than were obtained with the TBSM.

Model constants and statistical information for the Modified TBSM are given in Table 2.

The number density distributions $n(z)$ in the TBSM and Modified TBSM are shown in figure 5. It is seen that, to get the agreement with measured S_v -values shown below, a larger standing crop is required. Also, the relative proportion of larger fish must be increased, as seen in figure (6a). These results imply that both the absolute values of fish density and the size ranges of fish caught with the IKMT are seriously biased. Corresponding swimbladder size pdfs are compared in figure (6b).

The relative increase in large swimbladder radii in the Modified TBSM has a substantial impact on the predicted levels of S_v at 3.85 and 15.5 kHz, as may be seen by comparing Figs. (3a) and (7a) and Figs. (3b) and (7b). These results indicate that the single scattering component VSSM can provide acceptable fits to measured S_v -profiles at frequencies where different size classes in the bladdered fish population are the dominant scatterers. This implies that the length-depth distribution of bladdered fish given by the Modified TBSM is very likely fairly

OA12N NUMBER DENSITY FOR THE TBSM AND MODIFIED TBSM

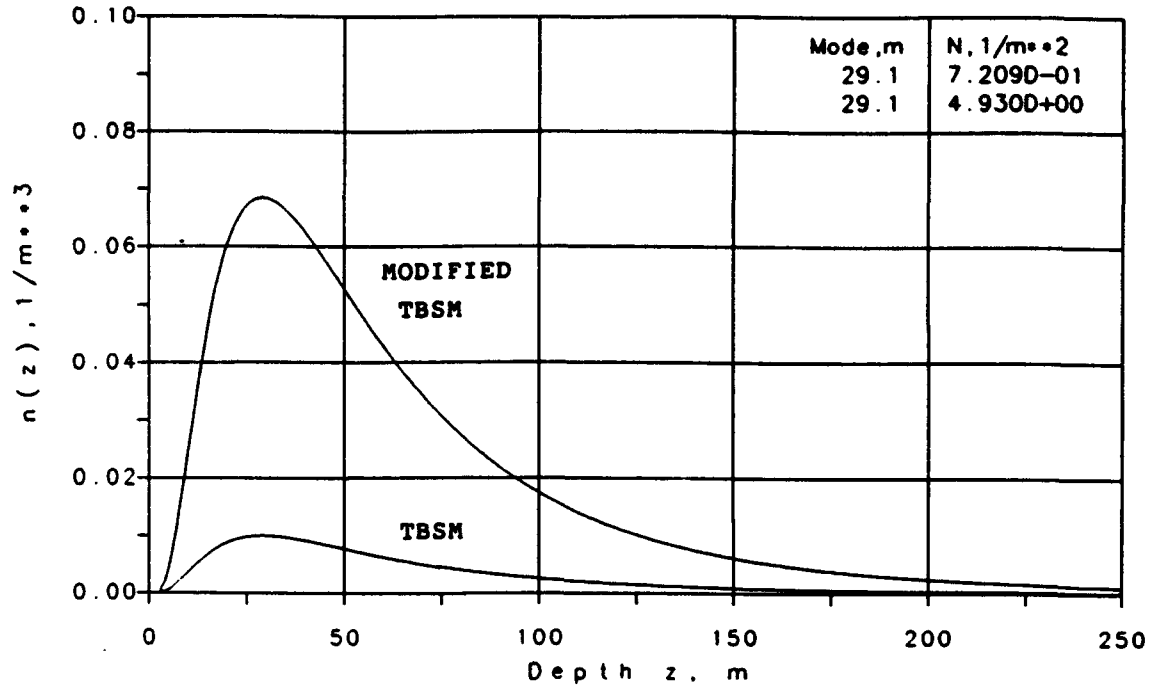


Figure 5. Number density distribution $n(z)$ for the TBSM; Modified TBSM. The characteristic density distribution $\hat{n}(z)$ is the same in each model but the respective standing crops are different: $N=0.72/m^2$ and $N=4.93/m^2$.

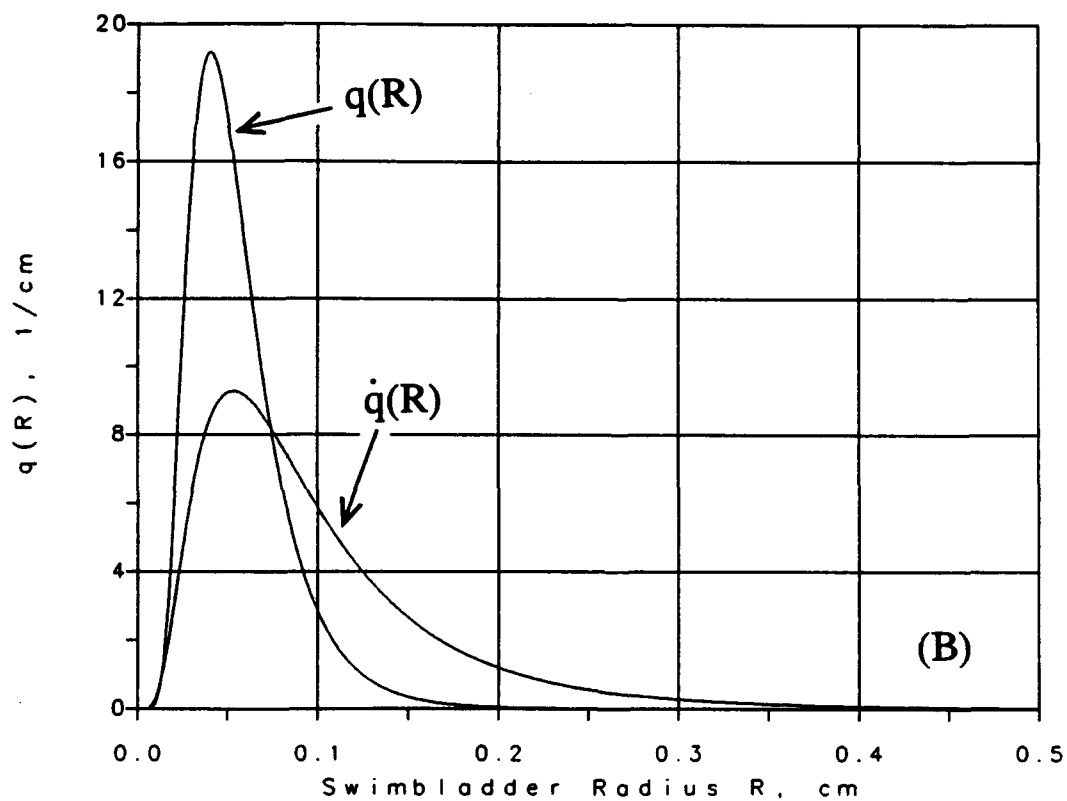
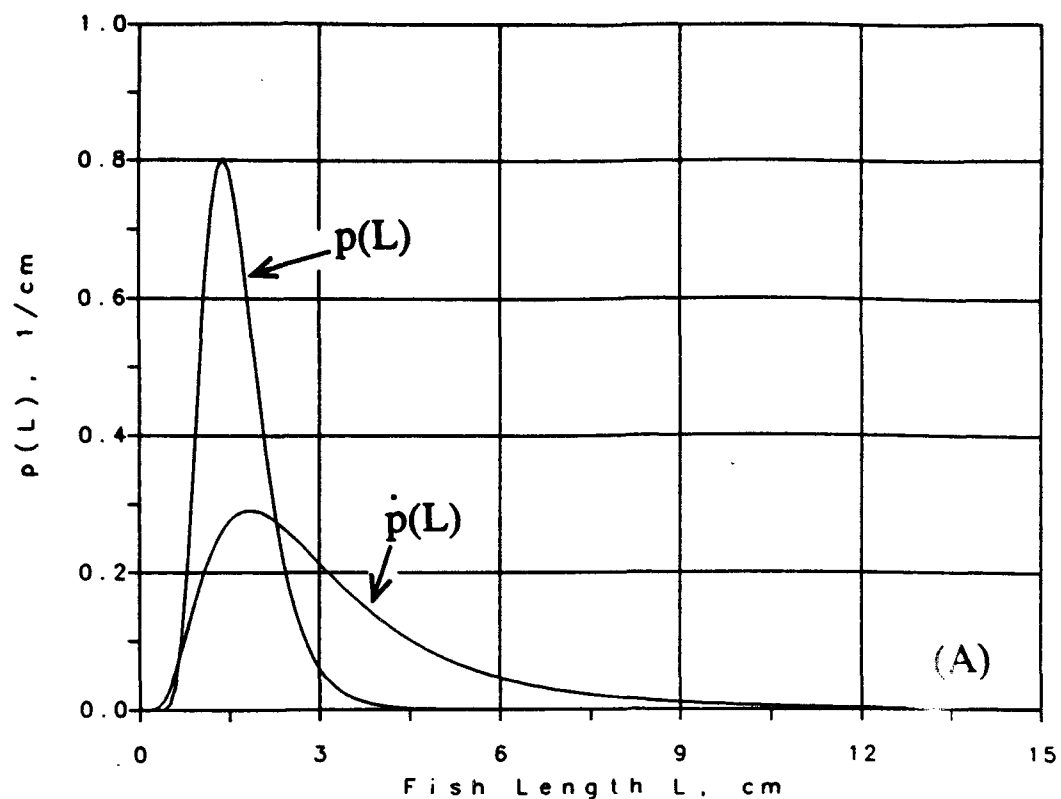
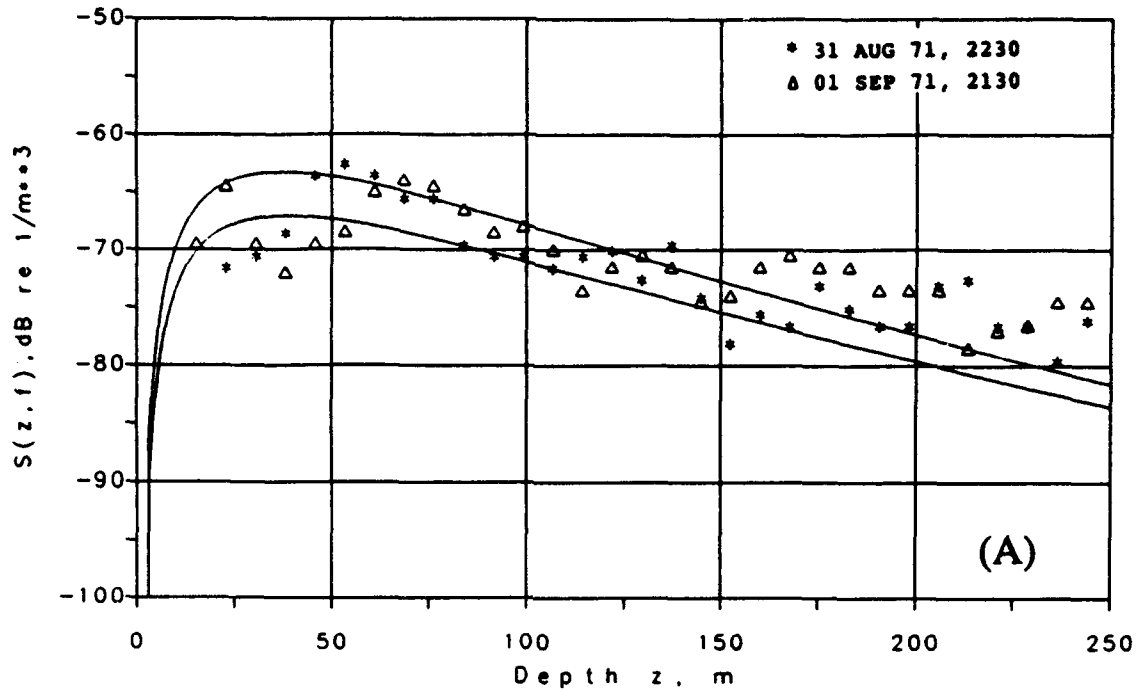


Figure 6. (a) Fish length pdfs $p(L)$; $\dot{p}(L)$ for the TBSM; Modified TBSM. (b) Corresponding swimbladder radius pdfs $q(R)$; $\dot{q}(R)$ for the two models.

OA12N MODIFIED TRAWL-BASED $S(z, f)$ PREDICTION MODEL, $f=3.85$ kHz
COMPARISON OF EXPERIMENTAL WITH MINIMUM AND MAXIMUM PREDICTED VALUES



OA12N MODIFIED TRAWL-BASED $S(z, f)$ PREDICTION MODEL, $f=15.5$ kHz
COMPARISON OF EXPERIMENTAL WITH MINIMUM AND MAXIMUM PREDICTED VALUES

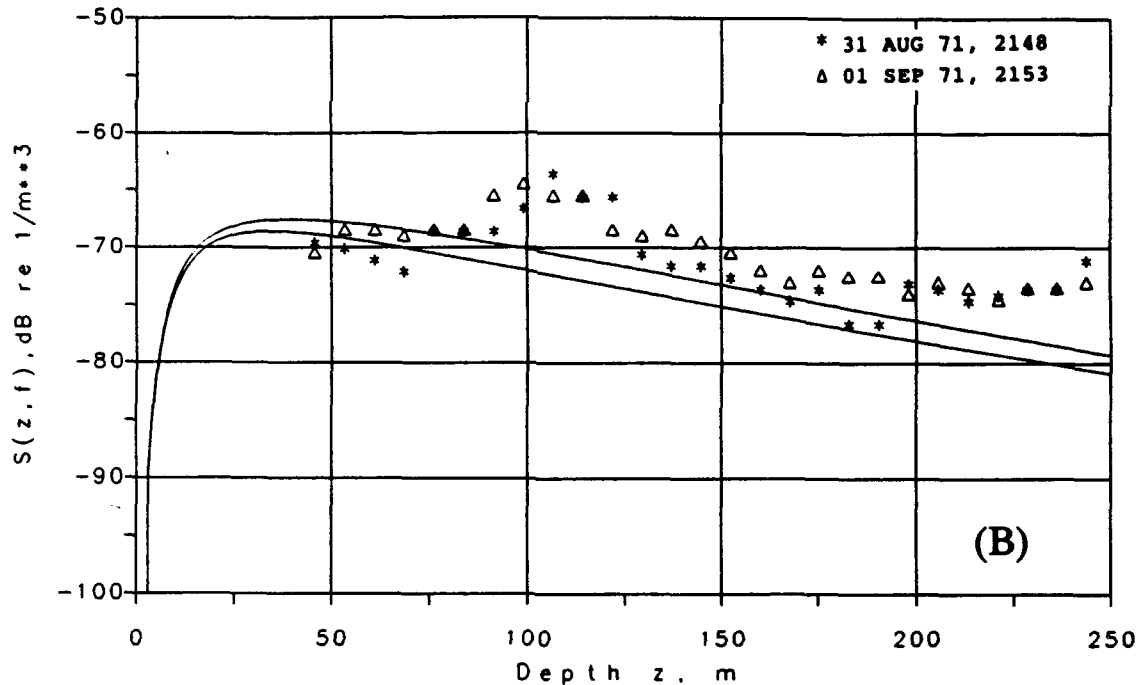
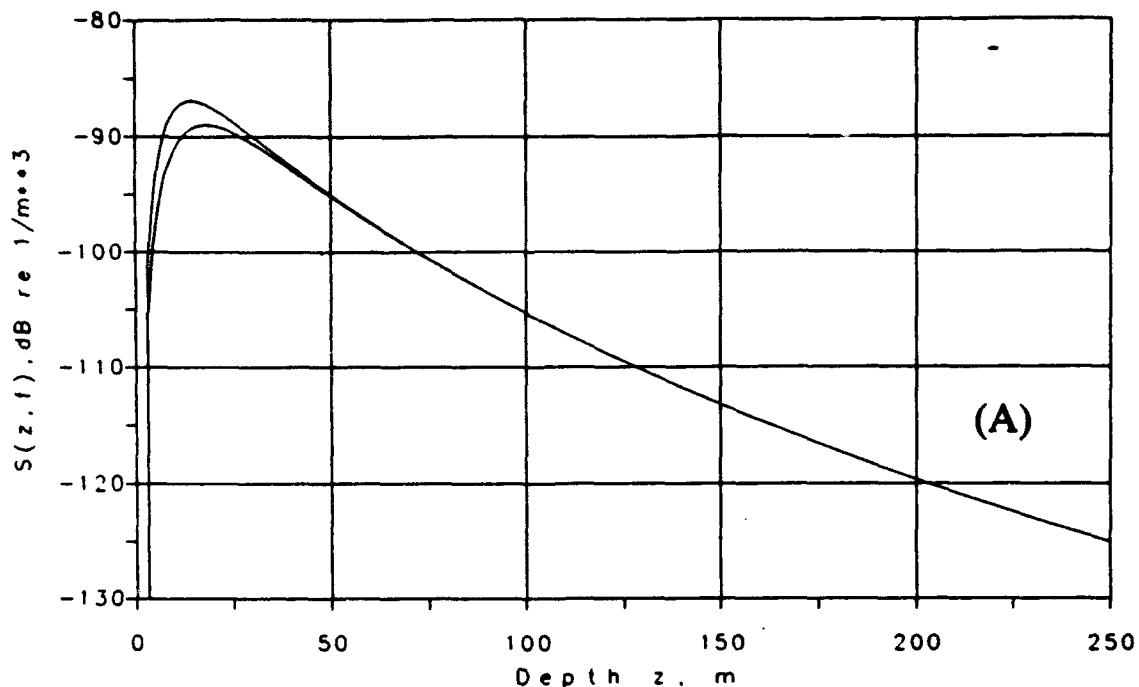


Figure 7. Modified TBSM predictions $S_v(z, f)_{Qmin}$ (lower curve) and $S_v(z, f)_{Qmax}$ (upper curve) compared with OA12N nighttime experimental profiles of Fisch and Dullea (1973) taken approximately 24 hours apart: Fig. (7a), $f=3.85$ kHz; Fig. (7b), $f=15.5$ kHz.

realistic, and that substantially more fish, particularly larger ones, are present than is indicated by discrete depth measurements with the IKMT.

Finally, predictions of $S_v(z,f)$ at 0.5 and 1.0 kHz are shown in figures (8a) and (8b). Comparison with the corresponding TBSM predictions in figures (4a) and (4b) shows a marked increase in predicted levels at both frequencies and also changes in profile shape, particularly in the 1.0 kHz profile, due to the inclusion of scattering contributions from larger fish. Since the resonance frequencies f_0 of the swimbladders of these larger fish are not very far above 0.5 and 1.0 kHz at shallow depths, differences in Q now have a perceptible effect on predicted values at these depths, as seen in figures (8a) and (8b).

MODIFIED TRAWL-BASED $S(z, f)$ MODEL PREDICTIONS USING MIN, MAX $Q(z)$: $f=0.5$ kHz



MODIFIED TRAWL-BASED $S(z, f)$ MODEL PREDICTIONS USING MIN, MAX $Q(z)$: $f=1.0$ kHz

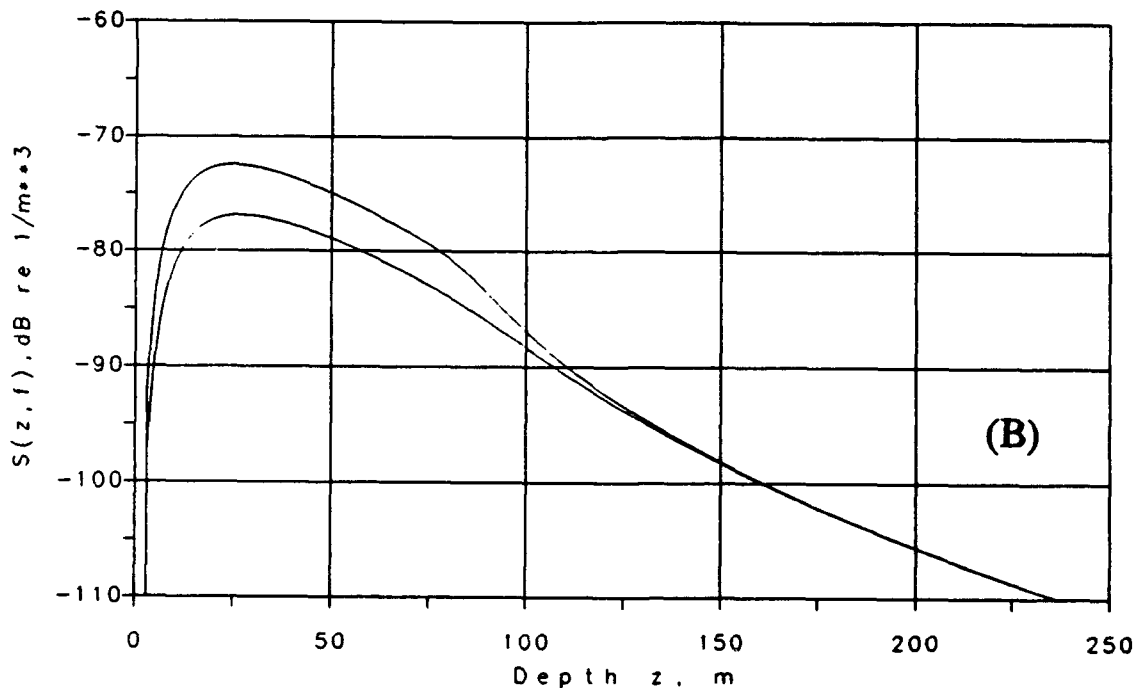


Figure 8. Predictions with the Modified TBSM of nighttime $S_v(z, f)_{Q_{min}}$ (lower curve) and $S_v(z, f)_{Q_{max}}$ (upper curve) for $f=0.5$ kHz (Fig. 8a) and $f=1.0$ kHz (Fig. 8b).

IV. Conclusions & Recommendations

In deep water, long range active sonars can be volume reverberation limited at night due to scattering from small mesopelagic swimbladdered fish present in near-surface waters. The effect of these scatterers on detection performance in a given propagation situation can be predicted with a general sonar model if a scattering strength profile $S_v(z,f)$ is available.

A parametric volume scattering strength model (VSSM) for predicting nighttime/daytime volume scattering strength profiles $S_v(z,f)$ in a deep water faunal province for frequencies below 20 kHz has been presented. The volume backscatter coefficient $s_v(z,f)$ is formulated as the product of a normalized volume backscatter coefficient representing the characteristic scattering properties of the province for a particular season, and the seasonal standing crop of bladdered fish scatterers which generally varies from year-to-year. The similarity of nighttime/daytime characteristic number density distributions of bladdered species groups in different ocean locations shown by Brooks and Saenger (1991) and the general similarity of scattering layers in the deep ocean suggests that the VSSM may prove useful for modeling $S_v(z,f)$ in many deep water areas.

To test the VSSM, a summer nighttime model for near-surface scattering has been developed for the North Sargasso Sea faunal province using Ocean Acre 12 IKMT trawl data and experimental $S_v(z,f)$ profiles. Results obtained are notable for several reasons. First, the simplest form of VSSM was found capable of

describing the 0-225 m portions of experimental S_v -profiles at 3.85 and 15.5 kHz. This could only be done, however, by modifying the model parameters calculated from trawl data that describe the length-depth distribution of scatterers caught with the IKMT. The need to substantially increase both the standing crop and the relative proportion of larger individuals in the model bladdered fish population in order to predict measured values of S_v at 3.85 and 15.5 kHz further confirms the long suspected limitations of discrete depth sampling with the 3-m IKMT. Second, the fact that dominant scattering contributions at 3.85 and 15.5 come from different size classes of the population suggests that the actual OA12N length-depth distribution of bladdered fish between the surface and 225 m is adequately modeled with this simple model. Finally, model predictions for lower frequencies suggest that, due to relatively strong scattering contributions from the larger mesopelagic fish, S_v -levels in the nighttime 0-50 m layer were as high as -75 dB at 1 kHz.

It is recommended that

1. The generality of the single scattering layer component VSSM for nighttime near-surface scattering be tested with bioacoustic data from other Ocean Acre experiments and available bioacoustic data from other deep water areas; and

2. Computer implementation of the VSSM be completed and documented to facilitate generation of deep water model $S_v(z,f)$ profiles for use in Navy sonar performance prediction models.

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Appendix A: Theoretical Representation for the Characteristic Fish Length-Depth Density Distribution of a Scattering Layer Component in the VSSM

As shown in Eq. (7), the fish length-depth density distribution $n(L,z)$ consists of a sum of N_i -weighted characteristic density distributions

$$(A1) \quad \hat{n}_i(L,z) = \hat{n}_i(z)p_i(L|z)$$

for scattering layer components $i=1,2,\dots$. We require an explicit parametric model for $n_i(L,z)$. In the present form of the VSSM, the model chosen is based on general mathematical and physical considerations, rather than specific assumptions as to the physical/statistical response of the scatterers to a particular environmental variable or variables. Let $x=\ln(L/l)$ and $\zeta=\ln(z/d)$ be logarithmic measures of fish length and depth, respectively, with $l=1$ cm and $d=1$ m. Dropping the subscript i in what follows for notational convenience, we propose the following

Fundamental Hypothesis: In terms of the length variate x and the depth variate ζ , the characteristic density distribution $g(x,\zeta)$ of a scattering layer component is bivariate normal with parameters $[\mu_x, \sigma_x, \mu, \sigma, \rho]$.

The properties of the bivariate normal density distribution are well known. (A simple exposition sufficient for present purposes may be found, e.g., in Cramér 1955.) The marginal x and ζ pdfs and the conditional x pdf of $g(x,\zeta)$ are normal, so the corresponding pdfs in the positive variates L and z are lognormal

(Aitchison and Brown 1957):

$$(A2) \quad p(L) = \lambda(L; \mu_x, \sigma_x^2),$$

$$(A3) \quad \hat{n}(z) = \lambda(z; \mu, \sigma^2), \text{ and}$$

$$(A4) \quad p(L|z) = \lambda(L; \mu_{x|\zeta}, \sigma_{x|\zeta}^2), \text{ where}$$

$$(A5) \quad \mu_{x|\zeta} = \mu_x + \rho \left(\frac{\sigma_x}{\sigma} \right) (\zeta - \mu) \text{ and}$$

$$(A6) \quad \sigma_{x|\zeta}^2 = \sigma_x^2 (1 - \rho^2).$$

For a general scattering layer component ($\rho \neq 0$), the conditional pdf $p(L|z)$ and its statistical properties change systematically with depth $z = de^\zeta$. For $\zeta = \mu$, $z = z_m = de^\mu$, the median of $\hat{n}(z)$. One can show that

$$(A7) \quad L_{\text{mode}}(z) = 1 \left[\text{EXP} \left(\mu_{x|\zeta} - \sigma_{x|\zeta}^2 \right) \right] \left(z/z_m \right)^{\rho \sigma_x / \sigma}$$

$$(A8) \quad L_{\text{median}}(z) = 1 \left[\text{EXP} \left(\mu_x \right) \right] \left(z/z_m \right)^{\rho \sigma_x / \sigma}$$

$$(A9) \quad L_{\text{mean}}(z) = 1 \left[\text{EXP} \left(\mu_x + (1/2) \sigma_x^2 \right) \right] \left(z/z_m \right)^{\rho \sigma_x / \sigma}.$$

The coefficient of variation $\eta_{L|z}$ of $p(L|z)$ (i.e., the standard deviation divided by the mean) has the constant value

$$(A10) \quad \eta_{L|z} = \left\{ \text{EXP} \left(\sigma_x^2 \right) - 1 \right\}^{1/2}.$$

For a simple scattering layer component ($\rho = 0$), the

conditional pdf $p(L|z)$, Eq. (A4), reduces to the marginal pdf $p(L)$, Eq. (A2), and all statistical properties of L are independent of depth. Formulas for the mode, median, mean, and coefficient of variation of $p(L)$ are obtained by evaluating the right hand sides of Eqs. (A7) - (A10), respectively, taking $\rho=0$.

Appendix B: Summary of the Simplified Andreeva Swimbladder Target Strength Model

The basic equations of the model (Andreeva 1964, 1972) are conveniently summarized as follows: Let

$$(B1) \quad G(z) = \left[1/(4\pi^2) \right] \left[(3\gamma P(z) + 4\mu_r)/\rho_f \right] ,$$

where $\gamma = c_p/c_v$ for the gas in the swimbladder, $P(z)$ is hydrostatic pressure at depth z , μ_r is the real part of the complex shear modulus $\mu = \mu_r + i\mu_{im}$ of fish tissue, and ρ_f is the density of fish tissue, approximately that of seawater. Also, letting

$$(B2) \quad b(z) = 1 - [2Q^2(z)]^{-1} ,$$

we may write the target strength $\tau_0(R, z, f)$ of a gas-filled swimbladder of radius R at depth z for frequency f as

$$(B3) \quad \tau_0(R, z, f) = R^6 / [R^4 - 2b(z)R_*^2 R^2 + R_*^4] ,$$

where

$$(B4) \quad R_*(z, f) = \sqrt{G(z)}/f ,$$

the "resonance radius". (At depth z , for an ensonifying frequency f , a swimbladder with radius R_* will be at resonance.) We note here that the "inverse" of this equation is

$$(B5) \quad f_0(R, z) = \sqrt{G(z)}/R ,$$

Andreeva's formula for the resonance frequency f_0 of a swimbladder of radius R at depth z .

Neglecting thermal damping, Andreeva's model for $Q(z)$ may be

written as

$$(B6) \quad [Q(z)]^{-1} = \eta_{r0} + \eta_{v0}$$

where the damping constant at resonance due to radiation losses is

$$(B7) \quad \begin{aligned} \eta_{r0} &= k_0 R = (2\pi f_0/c) R \\ &= (2\pi/c) \sqrt{G(z)} \quad , \end{aligned}$$

using (B5), and that due to viscous losses is

$$(B8) \quad \begin{aligned} \eta_{v0} &= 4\mu_{im} [3\gamma P(z) + 4\mu_r]^{-1} \\ &= \mu_{im} [\pi^2 \rho_f G(z)]^{-1} \quad , \end{aligned}$$

using (B1).

For practical calculations with the VSSM, we use the hydrostatic formula for $P(z)$ and the values $P(0)=1.013(10^6)$ dyn/cm², $\rho_w=1.025$ g/cm³, $g=980.6$ cm/s², $\gamma=1.40$ for air, $\rho_f=1.08$ g/cm³, $c=1.521(10^5)$ cm/sec. R and R_* are in cm, f in kHz, τ_0 in cm², and μ_r , μ_{im} are in dyn/cm². (In the VSSM, τ_0 from Eq. (B3) is expressed in m².) The computational expressions used for $G(z)$ and the dimensionless quantity $Q(z)$ are

$$(B9) \quad G(z) = 9.979(10^{-2}) + 9.382(10^{-8})\mu_r + 9.900(10^{-3})z \quad ,$$

in (cmkHz)² with z in m, and

$$(B10) \quad \begin{aligned} [Q(z)]^{-1} &= \eta_{r0} + \eta_{v0} \\ &= 4.131(10^{-2})\sqrt{G(z)} + (9.381)10^{-8}\mu_{im}[G(z)]^{-1} \quad . \end{aligned}$$

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